Reciprocal Distance Squared Method
A Computer Technique
for Estimating Areal Precipitation

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INTRODUCTION

Determination of watershed rainfall is basic to the calculation of other such hydrologic characteristics as runoff and infiltration. The accuracy of areal rainfall estimation inevitably influences the result of these other computations. This report presents a computer-oriented technique, Reciprocal Distance Squared (RDS), developed for the evaluation of areal precipitation. The method imposes a grid system on the area and calculates the amount of rainfall at each grid point by summing the products of gage weight and measured rainfal at nearby rain gages. Gage weights are computed as fractions of the reciprocal distance squared between the point and the rain gages. The amount of areal precipitation can be evaluated by integrating the grid point rainfall within the boundary of the area.[3]

The methods commonly used in calculating areal rainfall are the arithmetic mean, Thiessen, and the isohyetal method. Among these, the isohyetal method is generally considered the best, and the accuracy of the RDS method is judged on its ability to reproduce isohyetal results. Since the true areal rainfall is unknown, no objective method can be adopted for determining the superiority of the methods.

To reduce the laborious manual work and provide reproducible results, computer programs for calculating Thiessen weights and for drawing isohyetal maps have been presented by Diskin *(3,4)*[4] and Diskin and Davis *(5)*. Diskin *(3)* first suggested a Monte Carlo method for evaluating Thiessen weights. Later *(4)* he proposed a rectangular grid system method to improve the result. In the program to draw isohyetal maps, Diskin and Davis *(5)* constructed a network of lines connecting adjacent rain gages and then used linear interpolation to find coordinates of isohyetal points between two rain gage stations. By connecting points with equal amounts manually, the isohyetal map was drawn.

Rapid progress in the application of watershed modeling to solve hydrologic and water resources problems has created a demand for an effective, precise, and computer oriented means of evaluating areal rainfall. Several new approaches have been presented in recent years *(1, 7, 10, 11)*. The general procedures of these approaches can be defined as follow: A rainfall distribution equation is derived from the location of rain gages and rainfall measurements. A grid system is imposed on the watershed and rainfall at all grid points is calculated from the equation. Integrating rainfall at grid points with respect to the area within the watershed, divided by the watershed area, gives the average areal rainfall.

Utilizing a grid system to supplement hydrologic data where no measurement has been conducted is known as the grid square technique, and it has been used by Solomon and others *(11)* to estimate precipitation, temperature and runoff at Newfoundland, Canada. Later, Pentland and Cuthbert *(10)* applied the technique in generating synthetic steamflow of ungaged streams in the New Brunswick region of Canada. One strong advantage of the technique is the capability of using digital computers which can handle huge amounts of data. Most of the calculations for grid points can be performed as a matrix operation without any difficulty in a computer.

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[3] A similar technique is described by W. T. Sittner in an unpublished manuscript and outlined in "National Weather Service River Forecast System—Forecast Procedures," NOAA Tech. Memo. NWS HYDRO-14, 1967.

[4] Italic numbers in parenthesis refer to Literature Cited, p.13.

Many schemes have been suggested for determining the pattern of rainfall on a watershed area. After reviewing area-depth formulas, Court *(2)* suggested the bivariate Gaussian (or normal) distribution which provides elliptical isohyets as a means of describing the rainfall distribution pattern of storms. Assuming a polynomial distribution, Mandeville and Rodda *(7)* suggested the use of a trend-surface analysis to determine the best fit pattern. When the polynomial form was used in the distribution equation, Chidley and Keys *(1)* showed with a rectangular shaped watershed that the Thiessen type gage weight can be used to simplify the computation processes of areal rainfall.

There are some shortcomings in the approaches just outlined. First, the distribution pattern of the rainstrom is expressed in a mathematical form that could never be obtained precisely in actual storms. At best, the distribution equation indicates the averaged tendency of rainfall distribution of a storm but not the real distribution pattern. Second, it is necessary to determine the distribution equation for every rainstorm. Third, the calculation processes are irreversible, i.e., when a distribution equation has been established, it will usually not estimate the measured rainfall exactly at any of the rain gages. Finally, the distribution equation fits the overall trend of the rainfall pattern and smooths out local variations that may be important in the input of a watershed model.

Taking into account the deficiencies mentioned above, the RDS method considers the amount of rainfall at any ungaged point as a function of measured rainfall and distance from the point to the nearby rain gages alone. Thus, no rainfall distribution equation is required in the calculation. By limiting the affecting gages to the closest few gages and by assigning greater weight to the nearest gage, this method minimizes the tendency to smooth out the rainfall distribution pattern.

Two computer programs, written in Fortran language, were used for the computations. The examples were run on a terminal, at the North Appalachian Experimental Watershed, Coshocton, Ohio, which had access to General Electric's former Mark II computer time-sharing service.[5] Results are compared to those calculated from conventional methods. It is also shown that with a proper arrangement of the proposed method, Thiessen type gage weight can be calculated from the geometric factors of gage location and from the grid system.

RECIPROCAL DISTANCE SQUARED (RDS) METHOD

If a number of rain gages exist on a watershed and an estimate of the amount of rainfall at an ungaged point in the area is required, it is rational to make the estimate using the gages nearest the ungaged point and neglecting those at remote distances. Even among nearby gages, different factors such as the relative distances between gages and the point, altitude of each gage, and the slope and orientation of topography around each gage, results in each gage having a different true weight in the estimation. But in most cases, the strongest weight is from the nearest gage and weights reduce proportionately as the distance increases. The following assumptions were made to estimate the rainfall at an ungaged point.

First, impose a Cartesian coordinate grid system on the watershed so that the entire watershed area lies in the first quadrant. Then assume that the rainfall at any ungaged point (x, y) in a watershed can be determined by n number of nearby rain gages around the point where n is less than the number of rain gages available in the watershed. Also, assume that the rainfall at this point is porportional to the rainfall measured at the n rain gages and inversely proportional to the distances between the point and the rain gages. After testing the reciprocal distance in linear, square and cubic forms, the isohyetal map of the square form was found to most closely resemble that drawn by conventional methods. Thus using the squared form, the amount of rainfall, R, at point (x, y) can be expressed by

$$R = \left(\sum_{i=1}^{n} P_i/D_i^2\right) / \left(\sum_{i=1}^{n} 1/D_i^2\right) \qquad (1)$$

where P_i is the measured rainfall at gage i, D_i is the distance between point (x, y) and gage i, and n is the number of rain gages used in determining rainfall at the point (x, y).

If the point is close or coincides with one of the gages, say gage j, the reciprocal distance squared term of the gage j in Equation 1 becomes so large that other terms in the summation are trivial and negligible. Then, since the denominator and numerator of Equation 1 each contains the same term of the reciprocal distance squared, they cancel one another, and rainfall at point R becomes identical to that of gage j.

[5] Use of a trade name does not imply endorsement by the U.S. Department of Agriculture. It is used only for the purpose of providing specific information to readers.

The watershed boundary can be considered as a series of straight line segments. Then the area of a watershed can be calculated by summing up numerous small polygons of area $\triangle A$. If the apexes of successive angles in a polygon are assigned numbers from 1 to n, the coordinates of the apexes, (x_1, y_1), (x_2, y_2), ----, (x_n, y_n) can be read from the grid system. The polygonal area, $\triangle A$, can be calculated from

$$\triangle A = (x_1 y_n - x_n y_1) + \sum_{i=1}^{n-1} (x_{i+1} y_i - x_i y_{i+1}) \tag{2}$$

where x and y are the x coordinate and y coordinate of the apexes, respectively, and the subscripts denote the corresponding number assigned to each apex.

From Equation 1, the depth of rainfall at all points of each polygon can be calculated. If the area $\triangle A$ is chosen small enough, it can be assumed that the average rainfall in the area $\triangle A$ is a simple arithmetic mean of the rainfall at the apexes of the polygon. That is

$$\triangle P = \sum_{j=1}^{m} R_j/m \tag{3}$$

where $\triangle P$ is the average depth of rainfall in an area $\triangle A$, R_j is the calculated depth of rainfall at the apex j, and m is the number of apexes that compose the polygon. The volume of rainfall, $\triangle V$, in the area, $\triangle A$, is given by

$$\triangle V = \triangle P \triangle A = (\sum_{j=1}^{m} R_j/m) \triangle A \tag{4}$$

if $\triangle P$ is replaced by Equation 3.

If the volume of rainfall on a watershed, V, and the area of the watershed, A, are given, the average depth of area rainfall, P, on the watershed is

$$P = V/A. \tag{5}$$

Since the volume of rainfall in an area, $\triangle A$, is given in Equation 4, the volume of rainfall, V, on the watershed can be obtained by a summation of all volumes in the meshes. Therefore, Equation 5 can be rewritten as

$$P = \sum_{p=1}^{k} \triangle V_p/A \tag{6}$$

or

$$P = [\sum_{p=1}^{k} (\sum_{j=1}^{m_p} R_j/m_p) \triangle A_p] / A \tag{7}$$

where k is the number of mesh areas in the watershed and m_p and $\triangle A_p$ are the number of apexes and the area of mesh p, respectively.

The amount of rainfall, R_j, in Equation 7 at each apex, j, is calculated by Equation 1. Substituting in Equation 7,

$$P = \sum_{p=1}^{k} \langle \sum_{j=1}^{m_p} [(\sum_{i=1}^{n} P_i/D_i^2) / (\sum_{i=1}^{n} 1/D_i^2)]_j / m_p \rangle \triangle A_p / A. \tag{8}$$

If Equation 8 is completely expanded, it can be seen that every term consists of P_i multiplied by a function of D_i, m_p, $\triangle A_p$ and A. Considering any area, $\triangle A_p$, in the watershed, the number of corner points, m_p, is a fixed number. Also the distances from the corner points to any of the rain gages are constants. The sum of reciprocal of distance squared in the innermost parenthesis, $\sum_{i=1}^{n} 1/D_i^2$, is a constant. The coefficients of all P_i terms, therefore, become constants. Combining similar P_i terms, Equation 8 can be rewritten as

$$P = \sum_{i=1}^{n} W_i P_i \tag{9}$$

where W_i is a function of the geometric factors, D_i, m_p, $\triangle A_p$ and A, which are all constants. Equation 9 actually is of the same form as the Thiessen weight method, i.e. the areal rainfall is the summation of the products of gage weight and measured rainfall. Once the weights of the rain gages have been calculated, the areal rainfall can be obtained easily even with a desk calculator.

DESCRIPTION OF THE COMPUTER PROGRAMS

Because of limitations on the capacity of the available computer, two programs were written. The first program (Program A) provides grid point rainfall for drawing an isohyetal map, calculates the area of the watershed, and calculates the areal rainfall for a single event. The second program (Program B) calculates areal rainfall from Equation 9 for a series of events after first calculating the weight of each station. Both programs' source code listings are in Appendixes A and B with flow charts. A detailed description for preparing the input data for the programs is given in Appendix C. Only the internal functions of the programs are explained here.

For convenience of description, three types of points are defined in the grid system. A grid point occurs wherever an x grid line intersects a y grid line, point A, as shown in figure 1. A boundary point occurs wherever the watershed boundary intersects a grid line, point B, figure 1. A break point occurs wherever the watershed boundary has an abrupt change in direction, point C, figure 1.

In Program A, after the data have been read in, rainfall at grid points, boundary points, and break points are calculated from Equation 1 and results are stored for later use.

The program next examines each square mesh in turn starting from the origin and moving up the first column, then back to the bottom of the next column to the right, and so forth. A check is made of which points are included in each mesh and which of these points are inside the watershed boundary.

Starting from the lower left-hand side grid point of a square mesh, the program determines whether this point is located inside or outside the watershed boundary. Only the inside points are registered for storage. Then a check is made for the existence of boundary points on the left-hand sideline of the mesh. If there are any, they will also be registered. These processes are repeated for the next grid point and the next sideline of the mesh in a clockwise direction until all four grid points and four sides of square mesh have been examined. If all the points are located outside the watershed boundary, the mesh will be dropped by assigning the area a value of zero. If all the grid points are inside the watershed boundary, there should be no boundary points in this mesh and the area is assigned a value of one. From the previous point rainfall calculations, the average volume of rainfall for this mesh can be quickly computed. If boundary points have been detected in the mesh, it is necessary to check any break points existing in the mesh. If break points are included, they are inserted between the two boundary points so that the clockwise order of points is maintained.

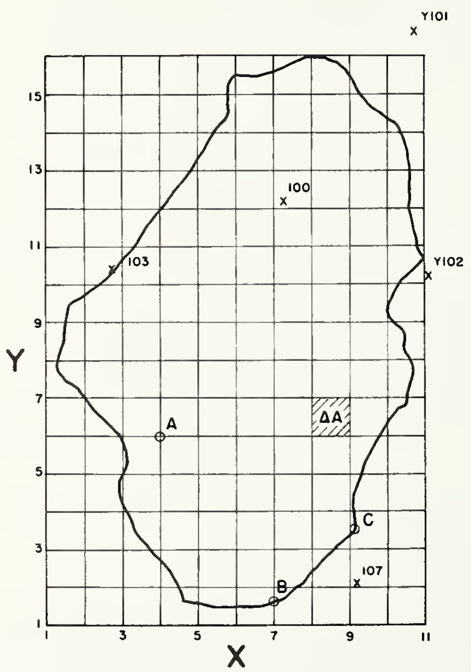

FIGURE 1. – Coshocton watershed No. 166 showing rain gage locations and grid system.

By using all the registered points in Equation 2, the area of a boundary mesh can be obtained, and it is always given as a fraction of one since the area of a complete square mesh inside the watershed was assigned as one. The average rainfall in the boundary mesh can also be computed from the information available in the previous point rainfall calculations. After every mesh in the grid system has been examined and calculated, the area of the watershed as well as the areal rainfall can be computed by summing the individual meshes.

Most parts of the second program are similar to that of Program A except that Program B does not calculate point rainfall and the average rainfall of a mesh. Instead, the geometric weights (coefficient part of Equation 8)of each mesh are distributed and accumulated into the corresponding gages to compile weights given in Equation 9. Once a mesh is selected, Program B counts the number of apexes, m_p, and calculates the area, $\triangle A$. After picking up a point in the mesh, the program calculates the fraction of the reciprocal squared distance of nearby n gages, multiplies the result by $\triangle A_p/m_p$, and accumulates the results for the proper gages. By repeating the same procedure for all points and meshes, the value accumulated for each gage station divided by the watershed area will give the weight of each station. The program then will read a rainfall event and compute areal rainfall from Equation 9. Since the last procedure can be repeated, this program can calculate as many rainfall events as one desires.

DETERMINATION OF MESH SIZE AND NUMBER OF GAGES USED IN CALCULATION

In determining the mesh size and the number of gages to be used in calculating rainfall at a grid point, accuracy and the amount of computation needed should be the main concern. Accuracy of computed areal rainfall generally increases with an increase in the number of grid points, but computer time increases accordingly. Therefore, selection of the size of the grid system is a compromise between the cost and accuracy of computation. More points will give a better picture of the rainfall pattern and more accurate isohyets, but a calculation of areal rainfall alone (not from an isohyetal map, but from integrating grid point rainfall) would need less points than the isohyetal map without reducing accuracy significantly.

The number of gages used to calculate rainfall at a grid point could vary from two gages, the minimum number required for applying Equation 1, to all the gages in the network. Since the summation of each fraction of the reciprocal distance square at all gages always totals one regardless of the number of gages used in the calculation, increasing the number of gages reduces the weight of nearby gages and the amount of rainfall computed tends to become more or less an average value. The effect of the local distribution pattern of the rainfall will be diminished. Also, increasing the number of rain gages increases computation time. Therefore, only a few of the available gages should be used at each grid point to preserve the local rainfall distribution pattern as well as to minimize the calculation. Computer resource units, an index of the amount of computation involved in each case, are listed in table 1 to give examples of cost which will depend upon suppliers charge per CRU. This cost does not include computer storage charges, terminal connect time, or input/output character charges.

The storm of July 4-5, 1969, in the Little Mill Creek Watershed, was used to test the effects of mesh size and the number of gages in calculating grid point rainfall. Mesh sizes of 2,000 ft., 4,000 ft., 6,000 ft., 8,000 ft., and 10,000 ft.

Table 1. – Computer resources units used in calculation

Number of gages	Number of grid points				
	143	42	25	16	16
2.	9.97	6.35	5.60	5.31	5.35
3.	11.13	7.03	6.09	5.74	5.78
4.	12.24	7.58	6.57	6.19	6.25
5.	13.37	8.20	6.95	6.59	6.68
6.	14.46	8.73	7.40	7.01	7.11
8.	16.72	9.85	8.34	7.82	7.93
10.	18.64	10.91	9.14	8.55	8.65
12.	20.76	11.93	9.95	9.28	9.39

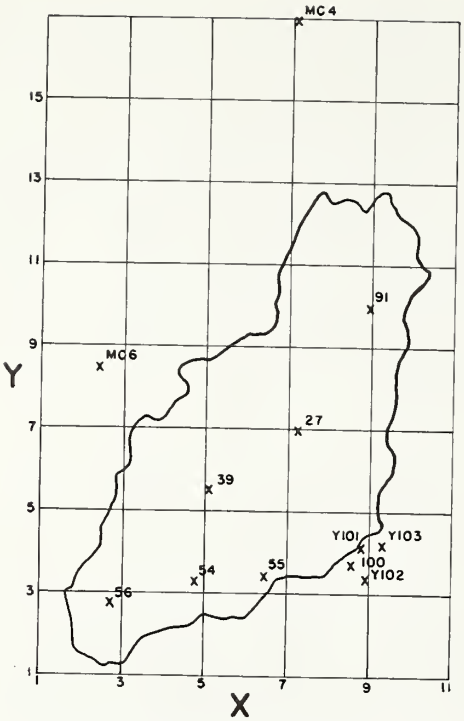

FIGURE 2. – Little Mill Creek watershed No. 97 showing rain gage locations and grid system.

were used which produced 143, 42, 25, 16, and 16 grid points around and inside the watershed. Also, the number of gages used in computing grid point rainfall varied from a minimum of two to all 12 gages. The location of rain gages with 2,000 ft. grid system on the Little Mill Creek Watershed is given in figure 2.

Areal rainfall calculated from the combinations of different arrangements are presented in table 2. Areal rainfall calculated from the isohyetal map, Thiessen weight, and arthmetic mean were 5.52 inches, 5.49 inches and 5.42 inches respectively. As the number of gages used at each grid point increased, the areal rainfall, regardless of the mesh size, decreased and became closer to the arithmetic mean as expected.

Table 2. – Areal storm rainfall calculated from different combinations of mesh size and number of gages used, Little Mill Creek, July 4-5, 1969

Number of gages	Areal rainfall[1] for grid system spacing of				
	2,000 feet	4,000 feet	6,000 feet	8,000 feet	10,000 feet
	Inches	*Inches*	*Inches*	*Inches*	*Inches*
2.	5.50	5.51	5.55	5.52	5.62
3.	5.49	5.49	5.53	5.51	5.60
4.	5.48	5.50	5.51	5.51	5.58
5.	5.47	5.48	5.50	5.48	5.57
6.	5.46	5.46	5.48	5.47	5.55
8.	5.44	5.44	5.46	5.44	5.53
10.	5.43	5.43	5.44	5.42	5.51
12.	5.41	5.41	5.42	5.41	5.49

[1] Rainfall from isohyetal map = 5.52 inches.

If all gages had equal weight, i.e. arithmetic mean, the weight of each gage would be 0.083 (1 ÷ 12). In general, gage weights tended toward the arithmetic mean value as the number of gages used at each grid point increases from 2 to 12. The larger the deviation from the mean for the 2 gage case, the greater the magnitude of change as gage numbers increase to 12. These relationships indicate the averaging effect of using many gages in the areal rainfall calculation. If we assume that the areal rainfall calculated from the isohyetal map, 5.52 inches, is correct, mesh sizes of 2,000 ft. and 4,000 ft. had better solutions when two gages were used (table 2), and 6,000 ft. mesh size for three or four gages. The 8,000 ft. and 10,000 ft. mesh size could not be judged for reasons that will be mentioned later. Two gages were, therefore, recommended in the calculation to preserve the local distribution pattern and to minimize the computer time.

The effect of mesh size in table 2 is not as clear as that of the number of gages. Mesh sizes of 2,000 ft. and 4,000 ft. show similar results, and mesh sizes of greater than 6,000 ft. do not show a clear cut pattern.

When a coarse grid system is imposed on a watershed, such as 8,000 ft. and 10,000 ft. mesh size, only a few grid points may be contained inside the watershed boundary. In this case, the location of the grid points can become important in the solution. A slight change in the grid system can result in a significant change in the solution. As the number of grid points increases, the location of the grid system becomes less important. Experience suggests that the following rule may be used in determining the appropriate mesh size: the number of grid points which fall within the watershed area should be about three to four times the number of rain gages available. The rule, however, should not be applied on a dense rain gage network as given later in the examples for Wayne County where less grid points are not only permissible but desirable.

EVALUATION OF RDS METHOD

Three gaged watersheds and one additional area were selected to illustrate the application and the validity of the RDS method. The first watershed, No. 166 of the North Appalachian Experimental Watershed, Coshocton, Ohio is shown in figure 1. The area of WS-166 is 79.2 acres. The locations of five rain gages are shown on the figure. A sixth gage (113), which is located at (4.70, -6.60), is not shown on the figure.

The second watershed is the Little Mill Creek Watershed No. 97 of Coshocton, Ohio, with an area of 4,580 acres. The boundaries of the watershed and rain gages are shown in figure 2.

The third watershed, No. 11, shown in figure 3 is part of the Walnut Gulch watershed in Arizona. It was used by Diskin and Davis *(5)* in their study. The area of the watershed is 2,035 acres.

A dense network of small, tube-type gages has been organized by McGuinness and Harrold *(8)* over an area of 1,500 square miles in northeast Ohio in cooperation with 1,700 volunteer observers. A storm measurement in Wayne County, Ohio, in which more than 200 observations were reported, were used in this report.

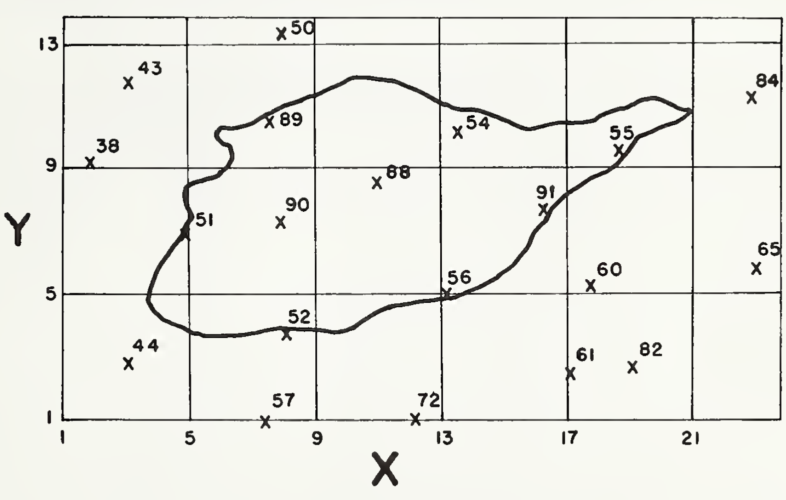

FIGURE 3. – Walnut Gulch watershed No. 11 showing rain gage locations and grid system.

Areal calculation

The area of a watershed was determined on the computer by summing up the meshes of the grid system which was assigned to the watershed. Giving the area of a square mesh a value of one, the areas of the watersheds were carefully counted manually. The results were compared with computer calculation given in table 3. Areas of the watersheds in acres are also shown. If the manual calculation is accepted as the true area, the error in all three cases is less than 1 percent. The computer calculation always gives a slightly smaller value than the manual method since the convex boundary lines are represented by a chord. The accuracy of the computer calculated area can be increased by increasing the number of break points.

Table 3. – Comparison of manual and computer calculated area
[Unit in mesh size]

Watershed name	Area	Manual	Computer	Error
	Acres			*Percent*
WS-166, Coshocton	79.2	90.43	90.23	0.22
Little Mill Creek, Coshocton	4,580.0	50.94	51.18	.47
Walnut Gulch, 11	2,035.0	80.85	80.20	.80

Interpolation of missing rainfall records

One simple application of the RDS method is interpolation of missing rainfall data by Equation 1. A commonly used method for interpolation is that of the U.S. Weather Bureau*(9)*. Three rain gages are selected as evenly spaced as possible around the rain gage where the record was missing. The normal annual rainfall of the three gages is compared to that of the data-missing gage. If all differences are less than ten percent, simple arithmetic mean is recommended. Otherwise, the normal-ratio method is used for the interpolation.

Records from rain gages 100, 103, 107, Y101, and Y102 of WS-166 (fig. 1) were used in an interpolation test. It was assumed that data from gage 100 were missing. Different methods were used to interpolate the missing data. Results as compared with measured rainfall are given in table 4. The arithmetic mean and normal-ratio method were calculated from rain gages 103, Y101 and Y102 which satisfies the Weather Bureau criteria. All gages were used for interpolation via the RDS method. All methods gave satisfactory results. The RDS method and the arithmetic mean with even gage distribution, however, show a closer match to the measured data.

The normal-ratio method implies that the storm distribution on an area follows the distribution pattern of normal annual precipitation. The arithmetic mean method, although it considers each event individually, assumes that all gages have the same weight which is true only when they are exactly evenly spaced. The RDS method not only considers individual events separately, but also gives more weight to the gage that is closest to the data missing station.

Table 4. – Comparison of missing rainfall records calculated by different methods

Date	Measured rainfall	RDS	Arithmetic mean: Even spacing[1]	Arithmetic mean: Uneven spacing[2]	Normal ratio
	Inches	*Inches*	*Inches*	*Inches*	*Inches*
April, 1967	3.09	2.96	2.97	2.87	3.07
July, 1967	6.38	6.55	6.58	6.52	6.81
March 28, 1967	1.14	1.06	1.06	1.05	1.09
June 8, 1967	.17	.17	.17	.18	.18
July 2, 1967	1.36	1.40	1.42	1.46	1.47
October 5, 1967	.55	.58	.58	.60	.60

[1] Calculated from rain gages 103, Y101 and Y102 (see fig. 3).

[2] Calculated from rain gages 103, Y101 and 107 (see fig. 3).

If gage 107 is substituted for gage Y102 to introduce an uneven spacing, the results become worse as shown in table 4. This indicates that the RDS method gives better results when the rain gages are unevenly spaced.

Areal rainfall calculation and isohyetal map

The storm of July 4-5, 1969 on the Little Mill Creek watershed was used for the areal rainfall calculation and isohyetal map drawing. The isohyetal map drawn by conventional methods (manual linear interpolation) is given in figure 4 as solid lines. The number attached to each gage is the measured rainfall. Gage MC 4 located at (7.08, 15.96) caught 6.61 inches of rainfall. This gage was not shown on the map but it was considered in drawing the isohyets.

From grid point rainfall, the isohyetal map was drawn manually as shown in figure 4 as dotted lines. Although the isohyetal maps drawn by the two different methods differ in detail, the general pattern of both maps is similar. The areal rainfall calculated by the RDS method, isohyetal map, Thiessen weight and arithmetic mean are given in the first row of table 5. All methods with the exception of the arithmetic mean gave about the same result.

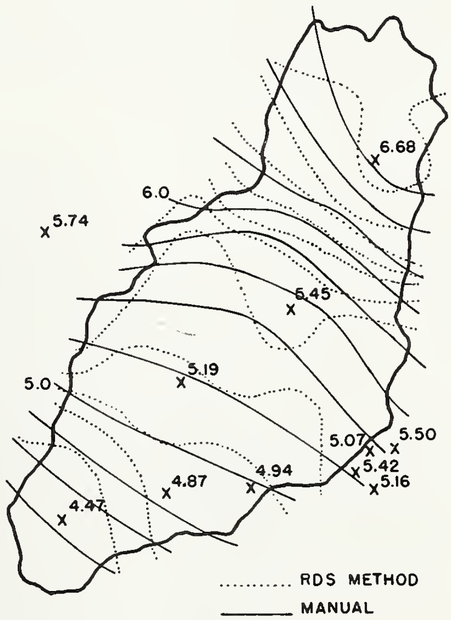

FIGURE 4. – Isohyetal map for storm of July 4-5, 1969, Little Mill Creek, Coshocton, Ohio.

Table 5. – Areal rainfall calculated from different methods

Watershed	Rainfall period	RDS	Isohyet	Thiessen	Arithmetic mean
		Inches	*Inches*	*Inches*	*Inches*
Little Mill Creek	July 4-5, 1969	5.50	5.52	5.49	5.42
Walnut Gulch	July 28, 1966	1.53	1.53	1.52	1.63
WS-166, Coshocton . . .	1967	34.53	34.53	34.48	34.45
	April, 1967	2.95	2.94	2.94	2.95
	July, 1967	6.41	6.42	6.40	6.52
	March 28, 1967	1.09	1.09	1.09	1.07
	June 8, 1967	.18	.18	.18	.18
	July 2, 1967	1.39	1.41	1.39	1.43
	Oct. 5, 1967	.59	.59	.59	.59

Table 6. — *Gage weights from Thiessen and RDS method, Little Mill Creek*

Method	Gage number											
	MC4	MC6	27	39	54	55	56	91	Y101	Y102	Y103	100
Thiessen	0	0.01350	0.23397	0.17203	0.07926	0.06693	0.12564	0.23984	0.02994	0	0.01350	0.02539
RDS	.01350	.02920	.21392	.16252	.09921	.06829	.10168	.22257	.04243	.00126	.02258	.02285

The gage weights for each rain gage calculated from the Thiessen and the RDS method are given in table 6. Gage MC 4 and Y102 have no effect on the areal rainfall calculation if the Thiessen method is used but, in the RDS method, both gages have a slight weight.

Diskin and Davis *(5)* used a computer to linearly interpolate the measured rainfall at two rain gages and drew an isohyetal map for the storm of July 28, 1966, on the Walnut Gulch watershed (fig. 5). Data from the same storm were used to test the RDS method. The isohyetal map based on the grid point rainfall is shown in figure 6. In general, the isohyetal maps drawn by the two different methods show fair agreement. The areal rainfall on the watershed, as shown in the second row of table 5, indicates that the RDS method and isohyetal method gave almost identical solutions whereas the other methods gave slightly different values.

The rain gage network in the northeast Ohio area measured several storms during its operation. One of them occurred on May 15, 1968, with a storm center located in Wayne County. Two hundred and seventy-five observers reported measurements with a maximum of 4.5 inches in the storm center. A manually drawn isohyetal map for the storm is shown as solid lines in figure 7. In the calculation of grid point rainfall, some modification was made in the computer program to reduce calculation time. Instead of calculating distances from a grid point to all of the rain gages, a small square region of plus and minus one grid unit in both the x and y direction from the grid point was delimited and only rain gages in that region were used to calculate the rainfall at that grid point. When the number of rain gages included in the region was fewer than the number of rain gages used to calculate the grid point rainfall, the region was expanded by one grid unit until the necessary number of rain gages was included in the region. Because of the less accurate measuring devices used in the rainfall measurement and the high density of the rain gages, four nearest gages were used, instead of two, to calculate the rainfall at a grid point. The isohyetal map from grid point rainfall is also shown in figure 7 as dotted lines. Area-depth curves, considering only the area inside Wayne County are shown in figure 8. The solid line is the result from the manually drawn isohyetal map, and the dotted line is the result from the isohyetal map drawn from grid point rainfall.

Most of the points calculated by the grid point method gave an excellent match with that of the manual method.

In a further investigation of the proposed method, annual, monthly, and daily rainfall for 1967 in the 79-acre watershed, 166 shown in figure 1, at Coshocton were used. Areal rainfall was calculated from a manually drawn

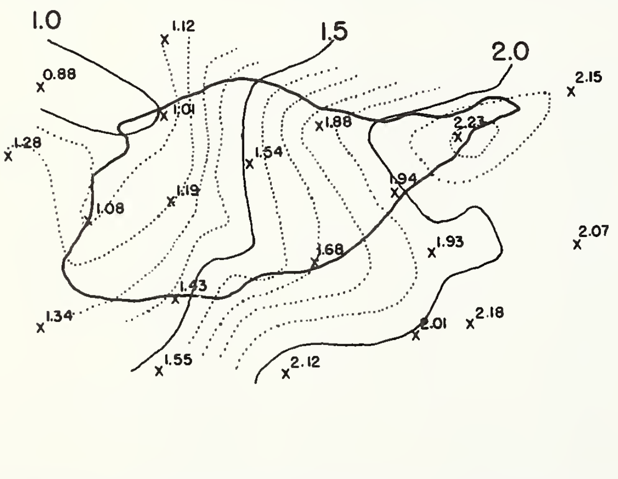

FIGURE 5. — Isohyetal map for storm of July 28, 1966, Walnut Gulch watershed, Arizona (from Diskin and Davis, 1970).

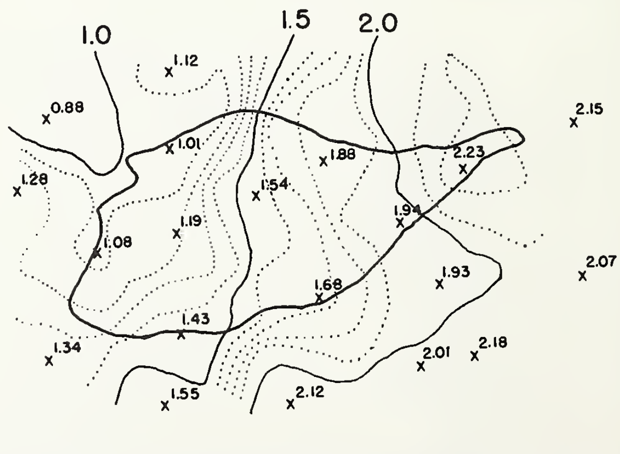

FIGURE 6. — Isohyetal map drawn from grid point rainfall, Walnut Gulch watershed, July 28, 1966.

isohyetal map, and by Thiessen weight, arithmetic mean, and the RDS methods. Results are presented in table 5 for annual rainfall of 1967, monthly rainfall for April and July 1967, and daily rainfall for the dates shown in the table.

The areal rainfall calculated by the RDS method provides a closer solution to that of the isohyetal method than the other methods.

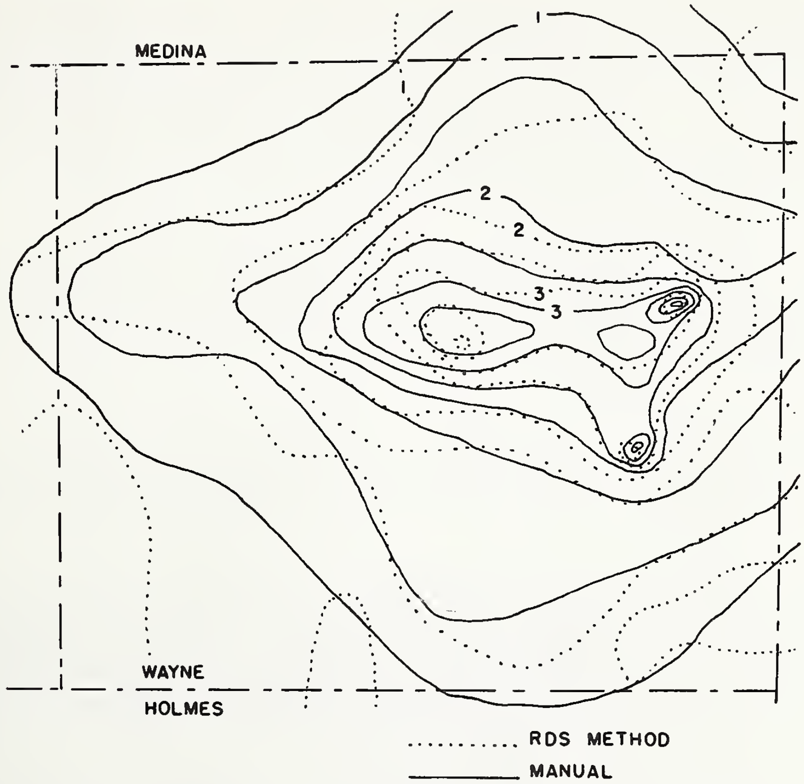

FIGURE 7. – Isohyetal map for storm of May 15, 1968, Wayne County, Ohio.

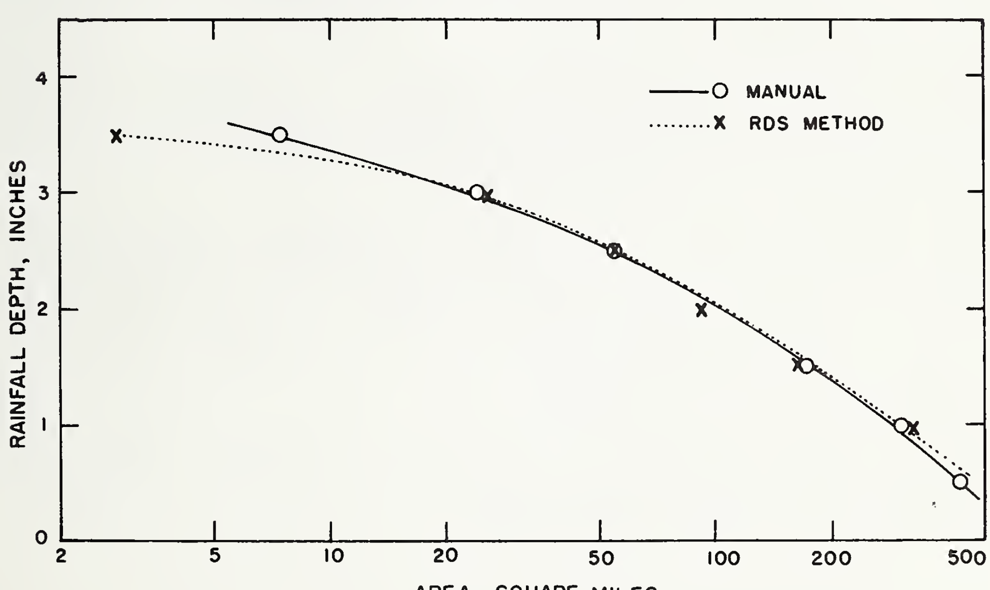

FIGURE 8. – Area-depth curves for May 15, 1968, storm in Wayne County, Ohio.

DISCUSSION

The Reciprocal Distance Square method is an attempt to make the best use of existing methods to develop a computer-oriented areal rainfall calculation method. Some advantages and deficiencies of the proposed method will be discussed in this section.

In this study, rainfall at a grid point is interpolated from the measurement of nearby gages rather than calculated from a surface trend equation. In preliminary trials, the bivariate normal equation, suggested by Court (2), was used to calculate areal rainfall as well as grid point rainfall. Although the method provided satisfactory results in area-depth calculations, it was unable to reproduce a satisfactory isohyetal map. The main deficiency of trend-surface fitting is that such methods fit a statistical average trend of the rainfall areal distribution pattern at the expense of local distribution tendency. RDS interpolation only considers local gages so that the area distribution patterns were constructed from section to section of the watershed without averaging out the local pattern. Linear interpolation was also tried, but the results were unsatisfactory.

Equation 1 is a rainfall interpolation equation where the amount of rain at a point was calculated from relative distances from the point to the nearby gages. It is also possible to consider other factors such as elevation differences, slope, and orientation of topography between the two points. It is not the purpose of this study, however, to develop such an interpolation equation. Rather, the purpose is to show that if the rainfall at a point can be interpolated from the nearby gages, areal rainfall can be estimated more accurately by using the technique given in this report.

The satisfactory results obtained in the current study indicate that distance is a major factor in a small areal rainfall calculation. In applying the proposed method, therefore, an area of 500 square miles is suggested as a limit. Another restriction should be on mountainous areas where the elevation of each point might have a significant effect on rainfall calculation.

Determination of mesh size and the number of gages used in calcualtions is another field that needs further investigation. The selection of mesh size depends on several factors, such as the size of the area or the watershed, the number of rain gages, the quality of rainfall data, the type of computer available, and the purpose of the study. As shown in the examples given in the previous section, too coarse a grid can provide an unstable solution. A finer mesh avoids such problems but at the cost of increasing the amount of computation. The criteria given in previous sections can be used as a general guide in the determination of the mesh size.

Two gages were used to compute grid point rainfall in this study with the exception of the dense rain gage network in Wayne County where four gages were used. Although a fixed number of gages were used in every case, it is possible to use a variable number of gages by assigning a radius of influence and using all the gages within that radius to compute rainfall at the grid point. Of course, the size of radius is another question that will arise if this method is used. Technically, this method is available.

The most important advantages of the new method are objectivity and consistancy. The data needed for the computation are rainfall amounts, coordinates of rain gages, boundary intersection points, and break points. Coordinates of points can be read easily without any human judgement being involved. All the calculations, regardless of whoever prepares the data, should result in the same answer.

Another advantage of the new method is the capability of utilizing more realistic rainfall input to many deterministic watershed models. For instance, in the USDA Hydrograph Laboratory Model/70 *(7)*, the watershed is grouped into several zones according to the land-capability classes of the watershed. Excess rainfall from a higher order zone is cascaded to the lower order zone. With the help of grid point rainfall calculated by the new method, rainfall for each zone can be computed individually. Or if desired, each zone can be divided into several sub-zones, and the rainfall can be calculated for each sub-zone so that the area distribution pattern of a storm can be retained in the watershed model. In addition, by properly assigning the geometric factors given in Equation 9, it is possible to calculate the gage weight for each zone. Making use of the gage weight and the break point rainfall data in rain gages, the break point rainfall for each zone can be composed. The input data to the model can preserve the important characteristics of rainfall—the time and areal distribution pattern.

CONCLUSION

A new approach in evaluating precipitation is proposed. Rainfall at a point is assumed to be proportional to the reciprocal of the distance squared from measuring gages to the point. Methods were developed to calculate areal rainfall, gage weight, grid point rainfall, and missing data. Two computer programs were written to carry out the calculations.

The new RDS method was applied on a variety of data where the area ranges from a few acres to approximately 500 square miles with the number of rain gages varying from six to several hundred. The results were compared with commonly used methods including the isohyetal map method, which was used as a basis for comparison. The RDS method was found to be close to that of the isohyetal method.

The RDS method with the help of the computer programs not only reduced the manual work involved, but it also provides an objective means of calculating areal rainfall. Once the gage weights for each rain gage have been calculated by the computer program, areal rainfall can be obtained with a desk calculator. With some modification, the method can estimate a partial areal rainfall or even construct an areal rainfall histogram to express the temporal and spatial distribution pattern of rainfall. In the application of mathematical watershed models on the hydrological and environmental problems, these data should provide better input data and improve the solutions.

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APPENDIX A
Computer Program A
for grid point rainfall and areal rainfall calculation

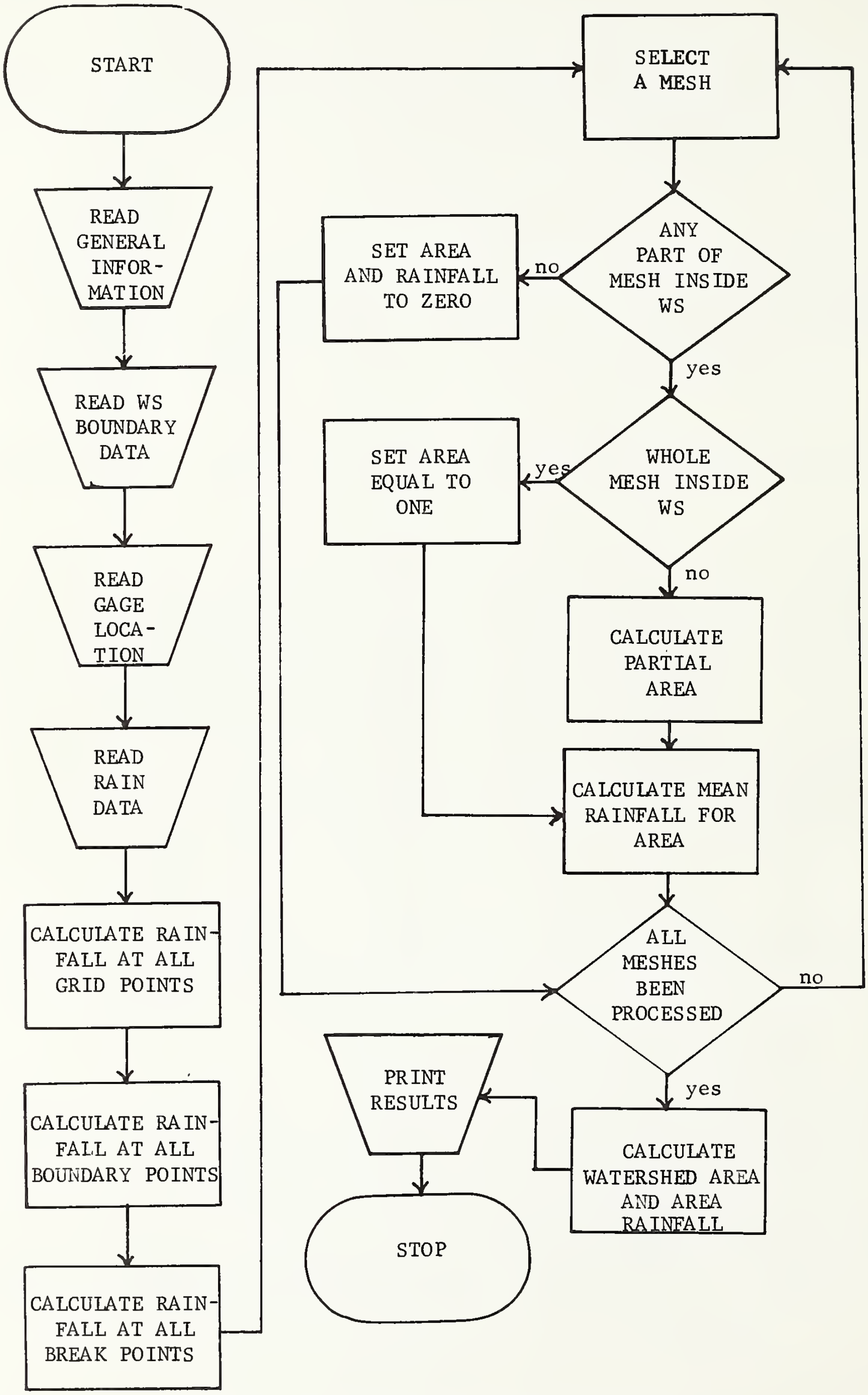

FIGURE 9. — Flow chart for calculating watershed area and rainfall, Program A.

```
C     THIS PROGRAM CALCULATES THE RAINFALL AT GRID POINTS AN
C     THE AREA RAINFALL
C
      DIMENSION YINT(22,7),XINT(22,7),BREK(100,2),XG(30),YG(30),
     &RG(30),R(22,22),RYINT(22,7),RXINT(22,7),RBRK(100),TEMPX(20),
     &TEMPY(20),TEMPR(20),KIND(20),KSID(20),A(22,22),RR(22,22)
      FILENAME F1,F2,F3
      F1="WTRSH"
      F2="GAGE"
      F3="RAIN"
      DATA NGAGE,NUSED,IMAX,JMAX,IYMAX,JXMAX,NBRK
     &/17,4,11,13,3,3,75/
C     READ WATERSHED DATA
      READ(F1,300) ((YINT(I,IY), IY=1,7), I=1,IMAX)
      READ(F1,300) ((XINT(J,JX), JX=1,7), J=1,JMAX)
      READ(F1,301) ((BREK(N,JB), JB=1,2), N=1,NBRK)
300   FORMAT(7F6.2)
301   FORMAT(2F6.2)
C     READ RAINGAGE LOCATION
      READ(F2,302) (XG(N), N=1,NGAGE)
      READ(F2,302) (YG(N), N=1,NGAGE)
C     READ MEASURED RAINFALL
      READ(F2,302) (RG(N), N=1,NGAGE)
302   FORMAT((10F6.2))
C     CLEAR ARRAYS
      DO 12 I=1,IMAX
      DO 12 J=1,JMAX
      R(J,I)=0.
 12   CONTINUE
      DO 13 I=1,IMAX
      DO 13 IY=1,IYMAX
      RYINT(I,IY)=0.
 13   CONTINUE
      DO 14 J=1,JMAX
      DO 14 JX=1,JXMAX
      RXINT(J,JX)=0.
 14   CONTINUE
      DO 17 N=1,NBRK
      RBRK(N)=0.
 17   CONTINUE
C     RAINFALL AT GRID POINTS
      PRINT 210
210   FORMAT(//2X,"CALCULATED RAINFALL AT GRID POINTS")
      DO 18 I=1,IMAX
      X=I
      TEMPX(L)=BREK(JB,1)
211   FORMAT(1H0)
      DO 18 J=1,JMAX
```

```
      Y=J
      R(J,I)=RAIN(NGAGE,X,Y,XG,YG,RG,NUSED)
      PRINT 212, R(J,I)
  212 FORMAT(1H&,F5.2)
   18 CONTINUE
C      RAINFALL AT BOUNDARY POINTS
      PRINT 213
      DO 19 I=1,IMAX
      IF(YINT(I,1).LE.0.) GO TO 19
      X=I
      YINT(I,1)=YINT(I,1)+1.
      II=YINT(I,1)
      DO 19 IY=2,II
      Y=YINT(I,IY)
      RYINT(I,IY)=RAIN(NGAGE,X,Y,XG,YG,RG,NUSED)
   19 CONTINUE
      DO 22 J=1,JMAX
      IF(XINT(J,1).LE.0.) GO TO 22
      Y=J
      XINT(J,1)=XINT(J,1)+1.
      JJ=XINT(J,1)
      DO 22 JX=2,JJ
      X=XINT(J,JX)
      RXINT(J,JX)=RAIN(NGAGE,X,Y,XG,YG,RG,NUSED)
   22 CONTINUE
C      RAINFALL AT BREAKING POINTS
      DO 23 N=1,NBRK
      X=BREK(N,1)
      Y=BREK(N,2)
      RBRK(N)=RAIN(NGAGE,X,Y,XG,YG,RG,NUSED)
   23 CONTINUE
C      SELECT POINTS WITHIN THE WATERSHED
      AREA=0.
      RARE=0.
      JB=1
      IMAX1=IMAX-1
      JMAX1=JMAX-1
      DO 190 I=1,IMAX1
      X=I
      XP=I+1
      DO 190 J=1,JMAX1
      Y=J
      YP=J+1
      L=0
      IF(YINT(I,1).EQ.0.) GO TO 30
      IY=2
      INT=YINT(I,1)
   10 IYP=IY+1
      IF(Y.LE.YINT(I,IY)) GO TO 20
      IF(Y.GE.YINT(I,IYP)) GO TO 11
      L=L+1
```

```
      TEMPX(L)=X
      TEMPY(L)=Y
      TEMPR(L)=R(J,I)
      KIND(L)=0
      GO TO 20
   11 IY=IY+2
      IF(IY.GT.INT) GO TO 30
      GO TO 10
   20 IF(YINT(I,IY).LT.Y) GO TO 21
      IF(YINT(I,IY).GT.YP) GO TO 30
      L=L+1
      TEMPX(L)=X
      TEMPY(L)=YINT(I,IY)
      TEMPR(L)=RYINT(I,IY)
      KIND(L)=1
   21 IF(IY.GE.INT) GO TO 30
      IY=IY+1
      GO TO 20
   30 IF(XINT(J+1,1).EQ.0.) GO TO 50
      JX=2
      JNT=XINT(J+1,1)
   31 JXP=JX+1
      IF(X.LE.XINT(J+1,JX)) GO TO 40
      IF(X.GE.XINT(J+1,JXP)) GO TO 32
      L=L+1
      TEMPX(L)=X
      TEMPY(L)=YP
      TEMPR(L)=R(J+1,I)
      KIND(L)=0
      GO TO 40
   32 JX=JX+2
      IF(JX.GT.JNT) GO TO 50
      GO TO 31
   40 IF(XINT(J+1,JX).LT.X) GO TO 41
      IF(XINT(J+1,JX).GT.XP) GO TO 50
      L=L+1
      TEMPX(L)=XINT(J+1,JX)
      TEMPY(L)=YP
      TEMPR(L)=RXINT(J+1,JX)
      KIND(L)=1
   41 IF(JX.GE.JNT) GO TO 50
      JX=JX+1
      GO TO 40
   50 IF(YINT(I+1,1).EQ.0.) GO TO 70
      IY=YINT(I+1,1)
      INT=2
   51 IYP=IY-1
      IF(YP.GE.YINT(I+1,IY)) GO TO 60
      IF(YP.LE.YINT(I+1,IYP)) GO TO 52
      L=L+1
```

```
      TEMPX(L)=XP
      TEMPY(L)=YP
      TEMPR(L)=R(J+1,I+1)
      KIND(L)=0
      GO TO 60
   52 IY=IY-2
      IF(IY.LT.INT) GO TO 70
      GO TO 51
   60 IF(YINT(I+1,IY).GT.YP) GO TO 61
      IF(YINT(I+1,IY).LT.Y) GO TO 70
      L=L+1
      TEMPX(L)=XP
      TEMPY(L)=YINT(I+1,IY)
      TEMPR(L)=RYINT(I+1,IY)
      KIND(L)=1
   61 IF(IY.LE.INT) GO TO 70
      IY=IY-1
      GO TO 60
   70 IF(XINT(J,1).EQ.0.) GO TO 90
      JX=XINT(J,1)
      JNT=2
   71 JXP=JX-1
      IF(XP.GE.XINT(J,JX)) GO TO 80
      IF(XP.LE.XINT(J,JXP)) GO TO 72
      L=L+1
      TEMPX(L)=XP
      TEMPY(L)=Y
      TEMPR(L)=R(J,I+1)
      KIND(L)=0
      GO TO 80
   72 JX=JX-2
      IF(JX.LT.JNT) GO TO 90
      GO TO 71
   80 IF(XINT(J,JX).GT.XP) GO TO 81
      IF(XINT(J,JX).LT.X) GO TO 90
      L=L+1
      TEMPX(L)=XINT(J,JX)
      TEMPY(L)=Y
      TEMPR(L)=RXINT(J,JX)
      KIND(L)=1
   81 IF(JX.LE.JNT) GO TO 90
      JX=JX-1
      GO TO 80
   90 IF(L.GT.1) GO TO 91
      A(J,I)=0.
      GO TO 190
   91 IF(KIND(1).EQ.1) GO TO 96
      DO 92 K=2,L
      IF(KIND(K).EQ.0) GO TO 92
      LOC=K+1
```

```
      GO TO 93
   92 CONTINUE
      A(J,I)=1.
      GO TO 110
   93 IF(JB.GT.NBRK) GO TO 100
      IF(BREK(JB,1).LT.X.OR.BREK(JB,1).GT.XP) GO TO 100
      IF(BREK(JB,2).LT.Y.OR.BREK(JB,2).GT.YP) GO TO 100
      DO 95 K=LOC,L
      KK=LOC+L+1-K
      KM=KK-1
      TEMPX(KK)=TEMPX(KM)
      TEMPY(KK)=TEMPY(KM)
      KIND(KK)=KIND(KM)
      TEMPR(KK)=TEMPR(KM)
   95 CONTINUE
   94 TEMPX(LOC)=BREK(JB,1)
      TEMPY(LOC)=BREK(JB,2)
      KIND(LOC)=3
      TEMPR(LOC)=RBRK(JB)
      L=L+1
      JB=JB+1
      LOC=LOC+1
      GO TO 93
   96 IF(JB.GT.NBRK) GO TO 100
      IF(BREK(JB,1).LT.X.OR.BREK(JB,1).GT.XP) GO TO 100
      IF(BREK(JB,2).LT.Y.OR.BREK(JB,2).GT.YP) GO TO 100
      L=L+1
      TEMPX(L)=BREK(JB,1)
      TEMPY(L)=BREK(JB,2)
      KIND(L)=3
      TEMPR(L)=RBRK(JB)
      JB=JB+1
      GO TO 96
C     AREA CALCULATION
  100 A(J,I)=FOFA(TEMPX,TEMPY,L)
  110 AREA=AREA+ABS(A(J,I))
C     RAINFALL CALCULATION
      RR(J,I)=FOFR(TEMPR,L)
      RARE=RARE+RR(J,I)*A(J,I)
  190 CONTINUE
      AMOUNT=RARE/AREA
      PRINT 201, AREA
  201 FORMAT(//2X,"WATERSHED AREA = ",F8.3," UNITS")
      PRINT 203, AMOUNT
  203 FORMAT(//2X,"AMOUNT OF RAINFALL ON THE WATERSHED = ",F8.3,
     &"INCHES")
      STOP
      END
      FUNCTION FOFR(R,L)
C     CALCULATE MEAN RAINFALL IN DELTA A
```

```
      DIMENSION R(20)
      XL=L
      P=0.
      DO 10 I=1,L
      P=P+R(I)
   10 CONTINUE
      FOFR=P/XL
      RETURN
      END
      FUNCTION FOFA(X,Y,N)
C      CALCULATE AREA OF POLYGON
      DIMENSION X(20),Y(20)
      A=0.
      NM1=N-1
      DO 10 I=1,NM1
      A=A+(X(I+1)*Y(I)-X(I)*Y(I+1))
   10 CONTINUE
      A=A+X(1)*Y(N)-X(N)*Y(1)
      FOFA=A/2.
      RETURN
      END
      FUNCTION RAIN(NOST,XJ,YI,X,Y,R,NUSED)
C      CALCULATE POINT RAINFALL
      DIMENSION X(300),Y(300),R(300),D(300),Z(300)
      DEN=0.
      UP=0.
      DO 10 K=1,NOST
      DX=(X(K)-XJ)*(X(K)-XJ)
      DY=(Y(K)-YI)*(Y(K)-YI)
      D(K)=DX+DY
      Z(K)=R(K)
   10 CONTINUE
      DO 20 K=1,NUSED
      KK=K+1
      DO 20 L=KK,NOST
      IF(D(K).LE.D(L)) GO TO 20
      TEMP=D(K)
      STOR=Z(K)
      D(K)=D(L)
      Z(K)=Z(L)
      D(L)=TEMP
      Z(L)=STOR
   20 CONTINUE
      DO 30 K=1,NUSED
      UP=UP+Z(K)/D(K)
      DEN=DEN+1./D(K)
   30 CONTINUE
      RAIN=UP/DEN
      RETURN
      END
```

APPENDIX B
Computer Program B
for gage weight and areal rainfall calculation

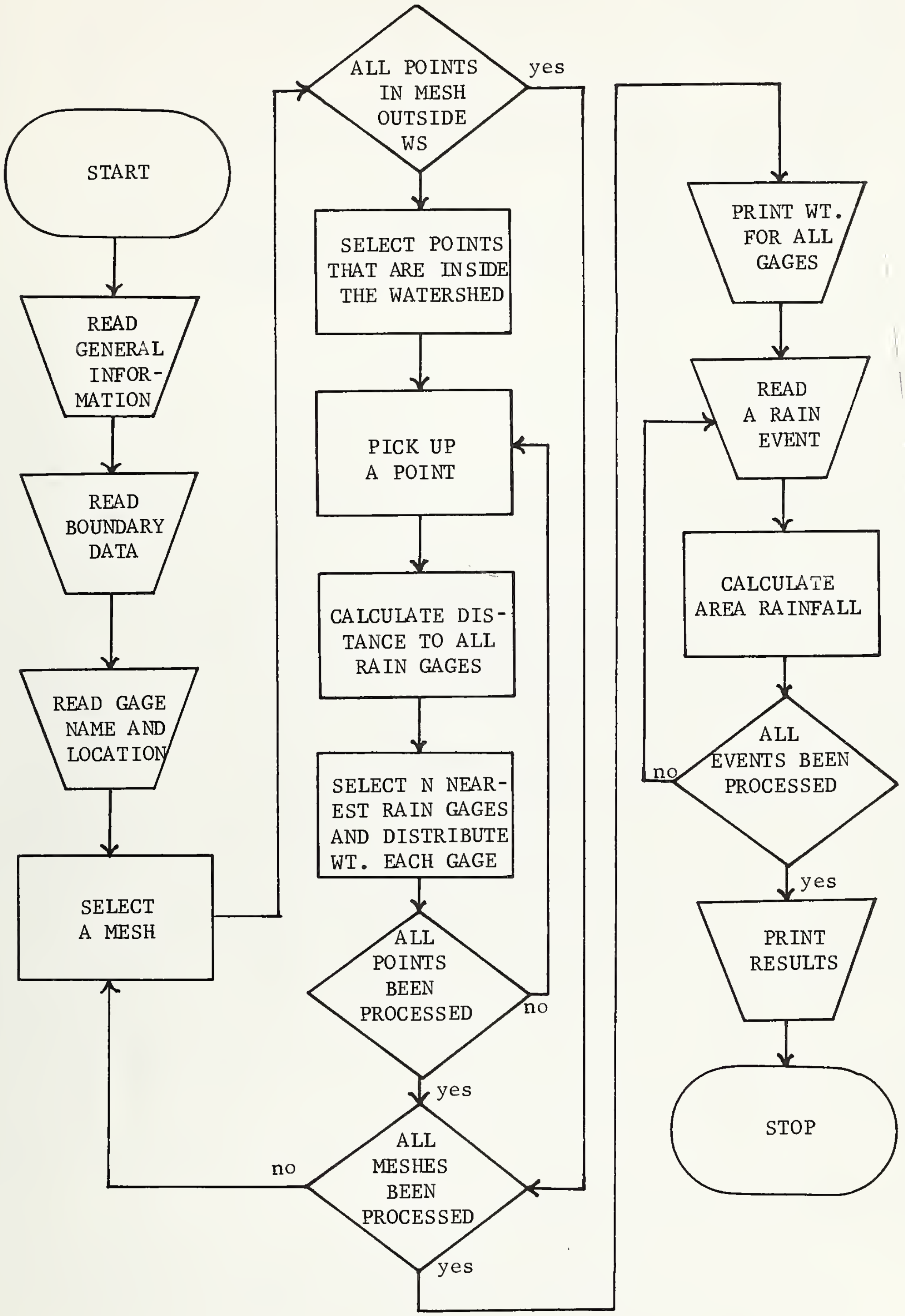

FIGURE 10. — Flow chart for calculating station weight and areal rainfall for a series of events, Program B.

```
C     THIS PROGRAM CALCULATES GAGE WEIGHT AND AREA RAINFALL
C
      DIMENSION YINT(22,7),XINT(22,7),BREK(100,2),XG(30),YG(30),
     &RG(30),NEFT(30),DD(30),WTG(30),GN(30),TEMPX(20),TEMPY(20),
     &KIND(20),A(22,22)
      FILENAME F1,F2,F3
      F1="WTRSH"
      F2="GAGE"
      F3="RAIN"
      DATA NGAGE,NUSED,IMAX,JMAX,IYMAX,JXMAX,NBRK
     &/17,4,11,13,3,3,75/
C     READ WATERSHED DATA
      READ(F1,300) ((YINT(I,IY), IY=1,7), I=1,IMAX)
      READ(F1,300) ((XINT(J,JX), JX=1,7), J=1,JMAX)
      READ(F1,301) ((BREK(N,JB), JB=1,2), N=1,NBRK)
300   FORMAT(7F6.2)
301   FORMAT(2F6.2)
      DO 13 I=1,IMAX
      IF(YINT(I,1).LE.0.) GO TO 13
      YINT(I,1)=YINT(I,1)+1.
 13   CONTINUE
      DO 14 J=1,JMAX
      IF(XINT(J,1).LE.0.) GO TO 14
      XINT(J,1)=XINT(J,1)+1.
 14   CONTINUE
C     READ RAINGAGE NAME AND LOCATION
      READ(F2,302) (XG(N), N=1,NGAGE)
      READ(F2,302) (YG(N), N=1,NGAGE)
      READ(F2,303) (GN(N), N=1,NGAGE)
302   FORMAT((10F6.2))
303   FORMAT((15A4))
C     SELECT POINTS WITHIN THE WATERSHED
      DO 12 N=1,NGAGE
      WTG(N)=0.
 12   CONTINUE
      AREA=0.
      JB=1
      IMAX1=IMAX-1
      JMAX1=JMAX-1
      DO 190 I=1,IMAX1
      X=I
      XP=I+1
      DO 190 J=1,JMAX1
      Y=J
      YP=J+1
      L=0
      IF(YINT(I,1).EQ.0.) GO TO 30
      IY=2
```

```
      INT=YINT(I,1)
10    IYP=IY+1
      IF(Y.LE.YINT(I,IY)) GO TO 20
      IF(Y.GE.YINT(I,IYP)) GO TO 11
      L=L+1
      TEMPX(L)=X
      TEMPY(L)=Y
      KIND(L)=0
      GO TO 20
11    IY=IY+2
      IF(IY.GT.INT) GO TO 30
      GO TO 10
20    IF(YINT(I,IY).LT.Y) GO TO 21
      IF(YINT(I,IY).GT.YP) GO TO 30
      L=L+1
      TEMPX(L)=X
      TEMPY(L)=YINT(I,IY)
      KIND(L)=1
21    IF(IY.GE.INT) GO TO 30
      IY=IY+1
      GO TO 20
30    IF(XINT(J+1,1).EQ.0.) GO TO 50
      JX=2
      JNT=XINT(J+1,1)
31    JXP=JX+1
      IF(X.LE.XINT(J+1,JX)) GO TO 40
      IF(X.GE.XINT(J+1,JXP)) GO TO 32
      L=L+1
      TEMPX(L)=X
      TEMPY(L)=YP
      KIND(L)=0
      GO TO 40
32    JX=JX+2
      IF(JX.GT.JNT) GO TO 50
      GO TO 31
40    IF(XINT(J+1,JX).LT.X) GO TO 41
      IF(XINT(J+1,JX).GT.XP) GO TO 50
      L=L+1
      TEMPX(L)=XINT(J+1,JX)
      TEMPY(L)=YP
      KIND(L)=1
41    IF(JX.GE.JNT) GO TO 50
      JX=JX+1
      GO TO 40
50    IF(YINT(I+1,1).EQ.0.) GO TO 70
      IY=YINT(I+1,1)
      INT=2
51    IYP=IY-1
      IF(YP.GE.YINT(I+1,IY)) GO TO 60
      IF(YP.LE.YINT(I+1,IYP)) GO TO 52
```

```
      L=L+1
      TEMPX(L)=XP
      TEMPY(L)=YP
      KIND(L)=0
      GO TO 60
   52 IY=IY-2
      IF(IY.LT.INT) GO TO 70
      GO TO 51
   60 IF(YINT(I+1,IY).GT.YP) GO TO 61
      IF(YINT(I+1,IY).LT.Y) GO TO 70
      L=L+1
      TEMPX(L)=XP
      TEMPY(L)=YINT(I+1,IY)
      KIND(L)=1
   61 IF(IY.LE.INT) GO TO 70
      IY=IY-1
      GO TO 60
   70 IF(XINT(J,1).EQ.0.) GO TO 90
      JX=XINT(J,1)
      JNT=2
   71 JXP=JX-1
      IF(XP.GE.XINT(J,JX)) GO TO 80
      IF(XP.LE.XINT(J,JXP)) GO TO 72
      L=L+1
      TEMPX(L)=XP
      TEMPY(L)=Y
      KIND(L)=0
      GO TO 80
   72 JX=JX-2
      IF(JX.LT.JNT) GO TO 90
      GO TO 71
   80 IF(XINT(J,JX).GT.XP) GO TO 81
      IF(XINT(J,JX).LT.X) GO TO 90
      L=L+1
      TEMPX(L)=XINT(J,JX)
      TEMPY(L)=Y
      KIND(L)=1
   81 IF(JX.LE.JNT) GO TO 90
      JX=JX-1
      GO TO 80
   90 IF(L.GT.1) GO TO 91
      A(J,I)=0.
      GO TO 190
   91 IF(KIND(1).EQ.1) GO TO 96
      DO 92 K=2,L
      IF(KIND(K).EQ.0) GO TO 92
      LOC=K+1
      GO TO 93
   92 CONTINUE
      A(J,I)=1.
```

```
      GO TO 110
   93 IF(JB.GT.NBRK) GO TO 100
      IF(BREK(JB,1).LT.X.OR.BREK(JB,1).GT.XP) GO TO 100
      IF(BREK(JB,2).LT.Y.OR.BREK(JB,2).GT.YP) GO TO 100
      DO 95 K=LOC,L
      KK=LOC+L+1-K
      KM=KK-1
      TEMPX(KK)=TEMPX(KM)
      TEMPY(KK)=TEMPY(KM)
      KIND(KK)=KIND(KM)
   95 CONTINUE
   94 TEMPX(LOC)=BREK(JB,1)
      TEMPY(LOC)=BREK(JB,2)
      KIND(LOC)=3
      L=L+1
      JB=JB+1
      LOC=LOC+1
      GO TO 93
   96 IF(JB.GT.NBRK) GO TO 100
      IF(BREK(JB,1).LT.X.OR.BREK(JB,1).GT.XP) GO TO 100
      IF(BREK(JB,2).LT.Y.OR.BREK(JB,2).GT.YP) GO TO 100
      L=L+1
      TEMPX(L)=BREK(JB,1)
      TEMPY(L)=BREK(JB,2)
      KIND(L)=3
      JB=JB+1
      GO TO 96
C      CALCULATES WATERSHED AREA
  100 A(J,I)=FOFA(TEMPX,TEMPY,L)
  110 AREA=AREA+ABS(A(J,I))
C      CALCULATES GAGE WEIGHT
      XL=L
      DO 120 K=1,L
      DO 121 N=1,NGAGE
      NEFT(N)=0
      DX=(XG(N)-TEMPX(K))*(XG(N)-TEMPX(K))
      DY=(YG(N)-TEMPY(K))*(YG(N)-TEMPY(K))
      DD(N)=DX+DY
  121 CONTINUE
      KOUNT=1
  122 N=1
  123 IF(NEFT(N).EQ.0) GO TO 124
      N=N+1
      GO TO 123
  124 NEFT(N)=1
      NN=N
      TD=DD(N)
      MM=N+1
      DO 125 M=MM,NGAGE
      IF(NEFT(M).GT.0) GO TO 125
```

```
      IF(TD.LE.DD(M)) GO TO 125
      NEFT(NN)=0
      NN=M
      NEFT(M)=1
      TD=DD(M)
  125 CONTINUE
      KOUNT=KOUNT+1
      IF(KOUNT.LE.NUSED) GO TO 122
      DEN=0.
      DO 126 N=1,NGAGE
      IF(NEFT(N).EQ.0) GO TO 126
      DEN=DEN+1./DD(N)
  126 CONTINUE
      DO 127 N=1,NGAGE
      IF(NEFT(N).EQ.0) GO TO 127
      UP=1./DD(N)
      DIS=UP/DEN
      PT=DIS/XL
      WTG(N)=WTG(N)+PT*A(J,I)
  127 CONTINUE
  120 CONTINUE
  190 CONTINUE
      DO 130 N=1,NGAGE
      WTG(N)=WTG(N)/AREA
  130 CONTINUE
      PRINT 214
  214 FORMAT(//2X,"CALCULATED WEIGHT FOR EACH RAIN GAGE")
      PRINT 215, (GN(N),WTG(N), N=1,NGAGE)
  215 FORMAT(5X,A4,F10.6)
C      READ MEASURED RAINFALL
      READ(F3,302) (RG(N), N=1,NGAGE)
C      CALCULATES AREA RAINFALL
      RAIN=0.
      DO 140 N=1,NGAGE
      RAIN=RAIN+RG(N)*WTG(N)
  140 CONTINUE
      PRINT 216, RAIN
  216 FORMAT(//2X,"AMOUNT OF RAINFALL = ",F6.3)
      STOP
  END
      FUNCTION FOFA(X,Y,N)
C      CALCULATES AREA OF POLYGON
      DIMENSION X(20),Y(20)
      A=0
      NM1=N-1
      DO 10 I=1,NM1
      A=A+(X(I+1)*Y(I)-X(I)*Y(I+1))
   10 CONTINUE
      A=A+X(1)*Y(N)-X(N)*Y(1)
      FOFA=A/2.
```

APPENDIX C

Preparation of input data

When the programs were written, some restrictions were placed on the input data to keep them as simple as possible to avoid confusion and to save labor. It is strongly recommended that anyone planning to use the program should read this section thoroughly and carefully.

The following materials should be available:

1. A watershed map that indicates the watershed boundary and available rain gages.
2. Graph paper of a size to cover the whole watershed map.
3. Rainfall records from the rain gages.

Before tracing the watershed map on the graph paper, it is necessary to examine the meshes that contain the watershed boundary so that the following situations do not occur. First, there should not be two or more separated watershed areas in a mesh as shown in figure 11-A by the shaded area. Second, if possible, limit the number of boundary points in the mesh to no more than two to avoid forming separted outside areas in a mesh as shown in figure 11-B.

Violations of the above rules can be eliminated by shifting and rotating the graph paper on the map. The first rule should always be obeyed but, if the second rule must be violated, no break points should be assigned to this mesh. The error in calculating watershed area caused by this situation is negligible.

After the watershed boundary and gage stations have been traced on graph paper, a Cartesian coordinate system, with origins at (1, 1) is drawn so that the whole watershed area lies within the first quadrant. The lowest point of the watershed boundary and the furthest point on the left hand side of the watershed boundary should come as close as possible to the axes. The gage stations, however, can be located in any quadrant. A grid system covering the entire watershed area can then be drawn as shown in figures 3, 4, and 5.

The input data required manually from the user at a terminal for both programs are almost identical, and, unless otherwise specified, are assumed applicable to both. The first set of data input contains general information and is given in the program as

DATA NGAGE, NUSED, IMAX, JMAX, IYMAX, JXMAX, NBRK

where

NGAGE is the total number of rain gages available for use,

NUSED is the number of rain gages that are going to be used in the calculation. This number must not exceed NGAGE and values of 2 to 4 are recommended,

IMAX is the maximum unit of the x grid line,

JMAX is the maximum unit of the y grid line,

IYMAX is the maximum number of boundary points on any x grid line,

JXMAX is the maximum number of boundary points on any y grid line, and

NBRK is the total number of break points.

From a file, F1, the program READs information concerning the watershed boundary with these statements:

```
READ (F1,300) ((YINT (I,IY), IY=1,7), I=1, IMAX)
READ (F1,300)((XINT(J,JX), JX=1,7), J=1,JMAX)
READ (F1,301) ((BREK(N,JB), JB=1,2), N=1,NBRK).
```

YINT (I,IY) are the boundary points where the boundary line crosses the x grid lines. If the boundary point coincides with a grid point, it is regarded as a boundary point. IY denotes the y-coordinate of the boundary points except that the first space (IY=1) is reserved to store the total number of the boundary points on the x grid line. I represents units of the x-axis and runs from I=1 to I=IMAX. Within a grid line, boundary points are arranged in an ascending order of the y values. If no boundary points exist in a grid line, zero should be used for at least the first column (IY=1). XINT(J,JX) are the points where y grid lines intercept the watershed boundary and should be prepared in the same manner as YINT(I,IY).

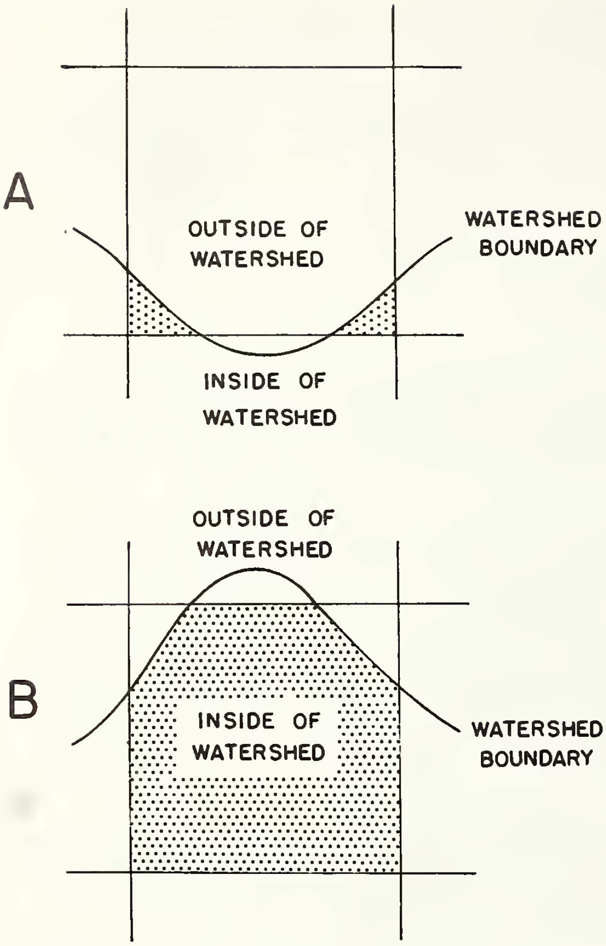

FIGURE 11. – Examples of undesirable situations in the grid system.

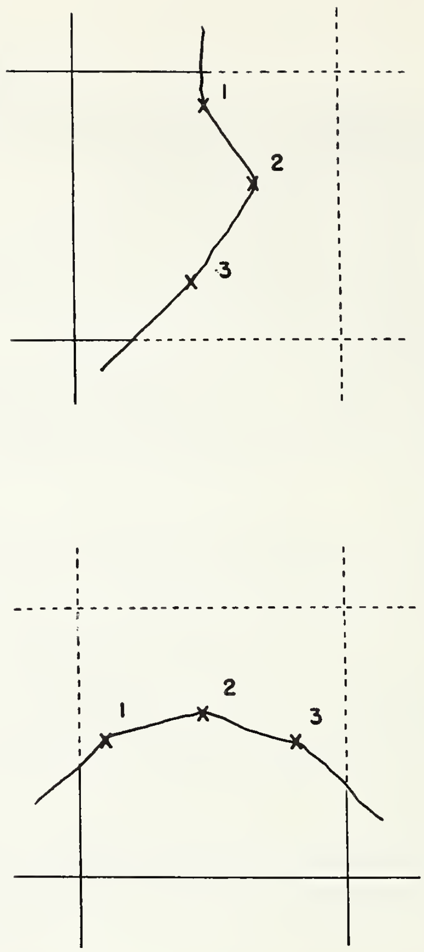

FIGURE 12. – Rules to assign the order of break points.

Break points are read in by the last read statement of BREK(N,JB). In selecting the break points, the second rule mentioned in the early part of this section should be observed. If a grid line is tangent to the watershed boundary, the tangential point is considered as a break point. The arrangement of the data is as follows. If there is more than one break point in a mesh, as shown in figure 12, the break points should be arranged numerically in a clockwise direction. In figure 12, the solid lines indicate the inside of the watershed and the dotted lines indicate the outside of the watershed.

The break points in each mesh are listed consecutively starting with the lowest mesh of the left most column of the grid system. After reaching the uppermost mesh of the column, change to the next column and start from the lowermost mesh again. Each break point will be registered in one line with x-coordinate value first and the y-coordinate value next.

The third part of the input data is information on the location of all rain gages read from the F2 file by

READ (F2, 302) (XG(N), N=1,NGAGE)

READ (F2, 302) (YG(N), N=1,NGAGE).

XG(N) is the x-coordinate and YG(N) is the y-coordinate of the rain gage. No order was assigned for arranging the data but the order of listing XG(N) and YG(N) must correspond. Each line contains 10 data points or less. In addition, Program B also needs the name or number of the gage stations. These are read from file F2 by

READ (F2,303) (GN(N), N=1,NGAGE).

An alphanumeric field of four characters was allotted to each gage, and the gages should be listed in the same order as the rain gage coordinates. No more than 15 data can be put on a line.

The last part of the input data are depth of measured rainfall at each gage. The data can be annual, seasonal, monthly, weekly, or daily rainfall, or rainfall for a special storm.

For Program A, data are read from file F2 with

```
READ (F2,302) (RG(N),N=1,NGAGE)
```

to read one event only. In Program B, data are read from file F3 with

```
READ (F3,302,END=999) (RG(N), N=1,NGAGE)
```

for continuous reading of several events. The data, of course, should be arranged in the same order as the other rain gage data.

It should be pointed out again that computer capacity was a factor when the programs were developed. Some modifications of the program will be required if it is to be used on a larger computer or for a larger size watershed. The main changes occur at DIMENSION, READ and PRINT statements. The teletype used limited output to 72 characters per line. Other output devices may allow up to 132 characters per line. Modification of the format is recommended to make best use of these larger input-output sizes. With some knowledge of programming or with the help of a consultant, this can be done without too much difficulty. No identification data such as the name of the watershed or the date of storm were given in the programs. If desired they can be added easily with several extra statements.

A few words on the output might be helpful although most of it is self-explanatory. In Program A, rainfall at grid points is given in the output. Grid point rainfall is printed out in matrix form so that the results can be used directly in drawing an isohyetal map. An example of the output is given in figure 13. The areal rainfall is given so that it is not necessary to measure the isohyetal map and calculate the areal rainfall.

In Program B, the results are more straight forward. First, it prints out the weight of each rain gage, and then it prints out the areal rainfall of each event.

```
CALCULATED RAINFALL AT GRID POINTS
4.56  4.54  4.53  4.56  4.94  5.27  5.64  5.69  5.70  5.68  5.66  5.93  6.03
4.55  4.50  4.49  4.55  4.73  5.53  5.65  5.73  5.73  5.70  5.66  5.94  6.07
4.57  4.50  4.48  4.59  4.85  5.42  5.59  5.71  5.72  5.69  5.69  5.99  6.13
4.64  4.65  4.74  4.76  5.10  5.14  5.43  5.60  5.69  5.68  5.98  6.07  6.23
4.71  4.90  4.88  4.94  5.17  5.20  5.28  5.33  5.61  5.62  6.15  6.20  6.63
4.87  4.94  4.96  4.96  5.14  5.28  5.38  5.39  5.88  6.11  6.23  6.65  6.63
4.77  4.86  4.97  5.07  5.07  5.40  5.45  5.59  6.01  6.31  6.39  6.66  6.64
4.77  4.77  5.22  5.28  5.21  5.34  5.42  5.78  6.33  6.57  6.55  6.66  6.64
4.76  4.93  5.13  5.13  5.28  5.29  5.47  6.11  6.54  6.68  6.62  6.67  6.65
4.99  5.01  5.07  5.41  5.37  5.32  5.48  6.25  6.51  6.61  6.58  6.67  6.65
4.99  5.00  5.00  5.32  5.34  5.32  5.31  6.27  6.42  6.50  6.51  6.67  6.66
AMOUNT OF RAINFALL ON THE WATERSHED = 5.50 INCHES
PROGRAM STOP AT 1445
USED    8.07 UNITS (Computer Resource Units)
```

Note: Orientation of this output was rotated 90 degrees of that of figure 4.

FIGURE 13. – Computer output of grid point rainfall, Little Mill Creek, July 4-5, 1969.

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